The Stellar IMF in Very Metal-Deficient Gas

Fumitaka Nakamura* and Masayuki Umemura**
*Niigata University and UC Berkeley, **University of Tsukuba

Abstract. In the context of the star formation through the fragmentation of an extremely metal-deficient protogalactic cloud, the gravitational collapse of filamentary gas clouds is explored with H_2 and HD chemistry. It is found by 1D hydrodynamical simulations that the cloud evolution is prescribed mainly by the initial density (n_0) and H_2 abundance ($x_{H_2,0}$). In particular, it turns out that the evolution of low-density filaments ($n_0 \lesssim 10^5$ cm^{-3}) bifurcates at a critical H_2 abundance of $x_{H_2,cr} \simeq 3 \times 10^{-3}$, beyond which HD cooling overwhelms H_2 cooling. The numerical results indicate that the stellar IMF is likely to be double-peaked and deficient in sub-solar mass stars, where the high mass peak of the IMF is around $10M_\odot$ or $10^2 M_\odot$, dependently on the initial density and H_2 abundance. If the gas in protogalactic clouds is photoionized by UV radiation or shock-heated, the H_2 abundance could exceed $x_{H_2,cr} \simeq 3 \times 10^{-3}$ by H^- reactions. Then, the high mass peak would be $O(10)M_\odot$.

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1. Introduction

Star formation in the early universe should have proceeded in very metal-deficient gas. When the metallicity is lower than $Z \lesssim 10^{-2} Z_\odot$, the thermal property of such metal-deficient gas is essentially the same as that of the metal-free gas because cooling by heavy metals is less effective than primordial molecular cooling. Among the primordial molecules, the importance of H_2 on the star formation in the early universe have been emphasized by many authors because they are the most abundant molecules in metal-free gas. H_2 molecules provide significant cooling through rotational and vibrational transitions which can lower the gas temperature down to a few hundred K and accordingly reduce the Jeans masses to stellar mass scales.

HD molecules are considered to be the second most abundant molecules in primordial gas during the post-recombination era. In spite of its low abundance ([HD/H_2] $\sim 10^{-3}$), HD can provide significant cooling at low temperature gas because HD has higher radiative transition probabilities and lower excitation temperatures than H_2. Therefore, HD cooling can lower the gas temperature down to $T \lesssim 100$K and accordingly, the Jeans mass is also reduced.

In this paper, we examine the effects of the HD cooling on the formation of stars in very metal-deficient gas, and elucidate the role of HD molecules for the stellar initial mass function (IMF) there.

2. Numerical Model and Methods

Our numerical model and method are the same as those of Nakamura and Umemura (2001a). We consider an infinitely long cylindrical gas cloud. We deal with the following 14 species: e, H, H^+, H^-, H_2, H_2^+, He, He^+, He^{++}, D, D^+, D^-, HD, and HD^+.

The density is assumed to be uniform along the cylinder axis and the radial distribution is expressed as $\rho = \rho_0 \left(1 + r^2/R_0^2\right)^{-2}$, where $R_0 = \sqrt{2fkT_0/(\pi G \rho_0 \mu)}$ is the effective radius, ρ_0 is the central mass density, T_0 is the initial gas temperature, μ is the mean molecular weight, and f is the ratio of the gravitational force to the pressure force. Our model is specified by four parameters: n_0, T_0, f, and the H_2 abundance $x_{H_2,0}$. It should be noted that a higher $x_{H_2,0}$ can be translated to a higher electron abundance of a parent cloud. This is because when the ionization degree of the parent cloud is higher, the H_2 molecules form more efficiently via radiative reactions of $\mathrm{H} + \mathrm{e} \rightarrow \mathrm{H}^- + h\nu$ and $\mathrm{H} + \mathrm{H}^- \rightarrow \mathrm{H}_2 + \mathrm{e}$.

We take into account the following thermal processes: (1) H cooling by radiative recombination, collisional ionization, and collisional excitation, (2) H_2 line cooling, (3) cooling by H_2 collisional dissociation, (4) heating by H_2 formation, and (5) HD line cooling.

3. Numerical Results

In this section, we examine the collapse of the filaments, taking into account the H_2 and HD cooling. As shown below, there is a critical initial H_2 abundance, above which HD cooling predominantly regulates the cloud evolution. Also, it is found that the HD cooling does not play an important role for high-density gas. Thus, the evolution of the primordial filaments is classified into three cases, depending upon the initial density and initial H_2 abundance; (1) low-density filaments with high H_2 abundance, (2) low-density filaments with low H_2 abundance, and (3) high-density filaments.

For low density filaments with $x_{H_2,0} \gtrsim 3 \times 10^{-3}$, HD cooling overwhelms H_2 cooling during the contraction, and the temperature descends down to $T \sim 50$ K accordingly. When the density reaches a critical density of HD ($n_{cr} \sim 10^{4-5}$ cm^{-3}), the cloud contraction tends to become quasistatic. Thus, the fragmentation will take place after that stage. For low density filaments with $x_{H_2,0} \lesssim 3 \times 10^{-3}$, because of the low x_{H_2}, the temperature stays a relatively high value at a few hundred K, and HD cooling does not play a role during the contraction. The contraction proceeds quasi-statically after the density reaches the critical density of H_2 ($n > n_{H_2,cr} = 10^{3-4}$ cm^{-3}). As for high density filaments with $n_0 \gtrsim 10^5$ cm^{-3}, the temperature stays at a relatively

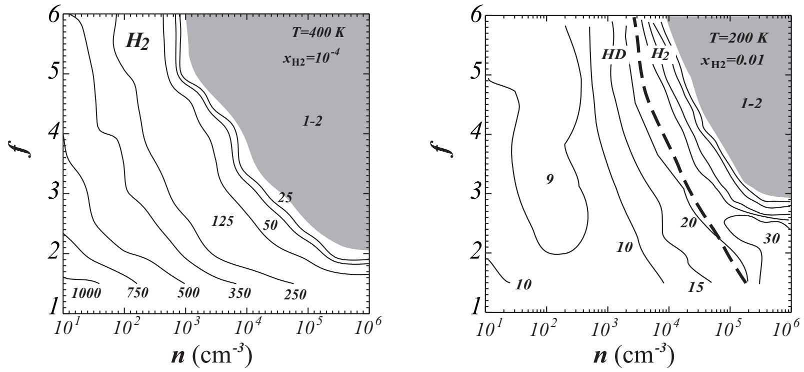

Figure 1. Mass distributions of the fragment derived from 1D simulations for the models with (a) $x_{\mathrm{H_2},0} = 1 \times 10^{-4}$ and (b) 1×10^{-2}, respectively. The abscissa and ordinate denote the initial central density and the parameter f, respectively. The solid lines denote the contours of the fragment mass which are labeled with adjacent numbers. The dashed lines show the lines at which the HD cooling rate is equal to H_2 cooling rate at the epoch of fragmentation. In the left regions of the dashed lines, HD cooling is more efficient than H_2 cooling.

high value because both H_2 and HD cooling is saturated, and therefore HD does not play a significant role for the thermal evolution. The contraction of such a high-density filament is accelerated by the effective three-body H_2 formation when the density reaches 10^{8-9} cm^{-3}. Then, the fragmentation is not expected to take place until the cloud becomes opaque to H_2 lines at the density of 10^{12-13} cm^{-3}.

Figures 1a and 1b show the distributions of the fragment mass derived from the 1D simulations (see Nakamura and Umemura (2001b) for more detail). For the models with $x_{\mathrm{H_2},0} < x_{\mathrm{H_2,cr}} \approx 3 \times 10^{-3}$ (Figures 1a), the mass distribution of the fragments is quite similar to the case without HD (Paper II), because HD cooling does not play an important role in the thermal evolution of the filaments. There is a steep boundary at $n \sim 10^4 - 10^5$ cm^{-3} in the mass distribution of the fragments for $f \gtrsim 3$. For the models with $n_0 \gtrsim 10^5$ cm^{-3}, the fragment masses take their minima at $1 \sim 2$ M$_\odot$, whereas, for the models with $n_0 \lesssim 10^5$ cm^{-3}, they are greater than $\sim 10^2$ M$_\odot$. [For the models with low densities ($n_0 \lesssim 10^5$ cm^{-3}), the contraction becomes quasistatic when the density reaches the critical density of H_2 and then linear density fluctuations can grow nonlinearly before the three-body H_2 formation becomes dominant ($n_0 \gtrsim 10^{8-9}$ cm^{-3}). In contrast, for the models with high densities ($n_0 \gtrsim 10^{5-6}$ cm^{-3}), the contraction time does not exceed the fragmentation time until the H_2 lines become optically thick at $n \sim 10^{12} - 10^{13}$ cm^{-3}.] This sensitivity in the fragment mass comes from the rapid increase in $x_{\mathrm{H_2}}$ due to the three-body reactions.

On the other hand, when $x_{\mathrm{H}_2,0} > 3 \times 10^{-3}$, HD cooling is more effective than H_2 cooling for low-density filaments. Thus, the maximum mass of low-density region reduces to a few tens $\mathrm{M}_\odot$. The minimum mass does not change because HD is not a dominant coolant in the evolution of dense filaments. Therefore, similarly to the models with low $x_{\mathrm{H}_2,0}$ the dependence of the fragment mass on n_0 exhibits a steep boundary around $n_0 = 10^4 - 10^5$ cm^{-3} for $f \gtrsim 3$.

The existence of a steep boundary in the mass distribution implies that the IMF is likely to be bimodal if both low-density and high-density filaments bear stars. The low-mass peak is around a few $M_\odot$, which is not sensitive to the abundance of H_2 formed in a parent cloud. The high-mass peak is $\approx 10^2 M_\odot$ if $x_{\mathrm{H}_2,0} \lesssim 3 \times 10^{-3}$, while it is $\approx 10 M_\odot$ if $x_{\mathrm{H}_2,0} \gtrsim 3 \times 10^{-3}$. In the next section, we discuss some implications of such bimodal IMF in the very metal-deficient gas.

4. Implications for Galaxy Formation

Recently, Susa and Umemura (2000) investigated the pancake collapse of pregalactic clouds under UV background radiation. They found that once the pancaking disk is shielded against external UV radiation, the H_2 molecules form efficiently via H^- reaction with abundant free electrons produced by UV background, and the resultant abundance reaches $x_{\mathrm{H}_2} \approx 3 \times 10^{-3}$. The pancake disks probably fragment into filaments in which stars would form. In this case, HD cooling is expected to become efficient in low-density filaments and then, the high mass peak of the IMF would go down to $\sim 10\ \mathrm{M}_\odot$.

The time-decreasing UV background radiation is also likely to influence star formation in dwarf galaxies which may be related to excess number count of faint blue objects observed in the Hubble Deep Field. Corbelli, Galli, and Palla (1997) studied the effects of the declined UV background on the thermal evolution of the protogalaxies. They found that there is a critical redshift of $z \sim 1 - 2$, below which the declined UV radiation is shielded by the gas disks where the H_2 abundance reaches 10^{-2} owing to high ionization degree by the UV radiation. The enhanced H_2 formation promotes a rapid transition toward the cold H I phase with $\sim 10^2$ K. Thus, in such dwarf galaxies, high mass peak of the IMF would decrease to $\sim 10\ \mathrm{M}_\odot$ owing to HD cooling.

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